TITLE OF THE INVENTION

SCANNING ELECTRON MICROSCOPE

BACKGROUND OF THE INVENTION

The present invention relates to a scanning electron microscope that scans the surface of a specimen with an electron beam and forms a two-dimensional electron image representing the shape or composition of the surface of the specimen through the detection of secondary signals produced by the specimen. More particularly, the present invention relates to a scanning electron beam microscope suitable for forming electron beam images of a high resolution at a high throughput by rapidly moving an observation point to tens of test positions on a semiconductor wafer as a specimen.

A scanning electron microscope (hereinafter abbreviated to "SEM") accelerates electrons emitted by an electron source of a heating electron emission type or a field electron emission type, collimates the accelerated electrons in a fine electron beam, i.e., a primary electron beam using an electrostatic lens or a magnetic field lens, scans a specimen two-dimensionally with the primary electron beam, detects secondary electrons generated by the specimen irradiated with the primary electron beam or secondary signal electrons, i.e.,

reflected electrons, and forms a two-dimensional electron image by applying intensities of detection signals as brightness modulating inputs to a cathode-ray tube (abbreviated to "CRT") that is scanned in synchronism with a scanning operation using the primary electron beam.

Device miniaturization has progressively advanced in the semiconductor industry in recent years, and optical microscopes for inspection in semiconductor device fabricating processes and test processes have been replaced by SEMs. The SEM uses an electron beam for dimension measurement and testing electrical operations. When observing an insulating specimen, such as a wafer that is used in the semiconductor industry, is observed with a SEM, a low acceleration voltage of 1 kV or below must be used not to charge the insulating specimen. Generally, the resolution of a general SEM using a low acceleration voltage of 1 kV is about 10 nm. As the miniaturization of semiconductor devices advances, demand for SEMs capable of forming images in a high resolution by using a low acceleration voltage has increased. A retarding system and a boosting system were developed and proposed in, for example, Japanese Patent Laid-open No. Hei 9-171791 to meet such demand. Those previously proposed systems enable observation in a resolution of about 3 nm under optimum conditions for observation.

SUMMARY OF THE INVENTION

When a SEM is used for the inspection of a
semiconductor device during semiconductor device
fabricating processes or a completed semiconductor device,
capability of rapidly moving an observation point to tens
of inspection positions on a semiconductor wafer is a
prerequisite of the SEM for the improvement of the
throughput of an inspection process. Therefore, a stage
capable of rapid movement has been used. However, the
positioning accuracy of the stage is on the order of
several micrometers. Mechanical control of the position
of the stage in an accuracy on the order of nanometers is
economically infeasible and is practically difficult in
respect of moving speed. Therefore, to position the stage
in a high accuracy higher than several micrometers, there
is adopted an image shifting system that shifts
electrically the coordinates of the scanning center of a
primary electron beam. In some cases, since the
coordinates are shifted by a distance as long as several
micrometers, the image shifting system employed in the
conventional SEM deteriorates resolution when the distance
of shift is great.

According to the present invention it is an object
of the present invention to provide a SEM capable of image

shifting an image without causing significant
deterioration of resolution.

With the foregoing object in view, the present
invention provides a SEM comprising: an electron source,
an image shifting deflector system including two
deflectors disposed respectively at upper and lower stages
to shift an irradiation position of a primary electron
beam emitted by the electron source on a specimen; and an
objective that focuses the primary electron beam; wherein
the objective has a lens gap opening toward the specimen,
and the deflectors disposed at the lower stage on the side
of the specimen forms a deflecting electric field in a
region corresponding to an effective principal plane of
the objective.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is an overall, schematic view of a SEM in a
preferred embodiment according to the present invention
provided with an image shifting deflector of a lower stage
provided with an electrostatic deflecting electrode;

Fig. 2 is a diagrammatic view of assistance in
explaining deflecting force and a conception of deflecting
force cancellation at the time of image shifting;

Fig. 3 is an overall, schematic view of a SEM
provided with a Wien filter that nullifies the off-axis

chromatic aberration;

Fig. 4 is an overall, schematic view of a SEM additionally provided with an image shifting deflector according to the present invention;

Fig. 5 is a top plan view of an image shifting deflector of an upper-stage according to the present invention;

Fig. 6 is a top plan view of an octupole electrostatic deflector employed as an image shifting deflector at a lower stage in the present invention;

Fig. 7 is a schematic view of an image shifting deflector employed in a SEM in a second embodiment according to the present invention;

Fig. 8 is a schematic view of an image shifting deflector employed in a SEM in a third embodiment according to the present invention;

Fig. 9 is a view of assistance in explaining the irregularity of brightness when a specimen is observed by a SEM in a high magnification;

Fig. 10 is a schematic view of assistance in explaining a path of secondary electrons when an image is shifted in a SEM; and

Fig. 11 is a typical view of a deflection range of an image shifting deflector.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 shows a SEM in a first embodiment according

to the present invention. A cathode 4 emits electrons

when a beam voltage 6 is applied across the cathode 4 and

an emission control electrode 5. The electrons thus

emitted are accelerated (decelerated in some cases) by the

emission control electrode 5 and an anode 8 held at a

ground voltage. An acceleration voltage for accelerating

a primary electron beam 1 is equal to an electron gun

acceleration voltage 7. The primary electron beam 1

accelerated by the anode 8 is gathered by a condenser lens

9. Angle of divergence of the primary electron beam 1 or

beam current is determined by a diaphragm 11 disposed

below the condenser lens 9. A knob 12 is operated for

centering the diaphragm 11.

The primary electron beam 1 having passed the

diaphragm 11 is deflected by image shifting deflectors 20

and 30 having a scanning deflection function for image

shifting, and is moved on a specimen 13 for

two-dimensional scanning. The deflecting intensities of

the deflectors 20 and 30 are adjusted so that the primary

electron beam 1 travels straight through an objective 10.

A deflection function for scanning and an image shift

deflecting function are provided by simultaneously

applying a scanning deflection component and an image

shifting deflection component to the deflectors 20 and 30

by a deflection control power supply 40 to input the

deflecting intensities of the deflectors 20 and 30.

A focusing magnetic field created by the objective

acts on the primary electron beam 1 so as to deflect the

primary electron beam 1 in directions perpendicular to the

direction of travel of the primary electron beam 1 to

deflect the primary electron beam for image shifting so

that the primary electron beam deviates greatly from the

optical axis of the objective 10. Thus, the deflection of

the primary electron beam 1 causes off-axis aberration.

Such off-axis aberration can be suppressed by a deflector

that deflects the primary electron beam 1 so as to cancel

deflection caused by the objective 10. However,

disposition of a deflector in the objective 10 is

subjected to many physical restrictions. This SEM employs

the objective 10 having a lens gap opening toward the

specimen, i.e., an objective having a lower magnetic pole

having an aperture greater than that of an upper magnetic

pole and capable of creating a maximum focusing magnetic

field in the vicinity of the specimen disposed below the

objective. Thus, the effective principal plane of the

objective is positioned on a level different from that of

the objective or on a level that places only few physical

restrictions to facilitate the disposition of an

electrostatic deflecting electrode. The SEM shown in Fig. 1 has an optical system of a short overall length because only the deflector 20 needs to be disposed between the condenser lens 9 and the objective 10.

The primary electron beam 1 is decelerated by a decelerating electric field created between the objective 10 and the specimen 13 by applying a negative retarding voltage 15 through a stage 14 to the specimen 13 and is collimated by the collimating action of the objective 10.

In this embodiment, the upper deflector 20 is a magnetic deflector and the lower deflector 30 is an electrostatic deflector. The upper deflector 20 may be an electrostatic deflector. Similarly, the lower deflector 30 may be a magnetic deflector. However, since only a narrow space is available in the vicinity of the objective 10, it is proper to use an electrostatic deflector as the lower deflector 30.

Image shifting deflecting intensity I_{IS} given to the upper deflector 20 by the deflection control power supply 40 is expressed by the following expression.

$$I_{IS} = K_1 \frac{\sqrt{V_{acc}}}{LM_{sem}}$$

where K_1 is conversion coefficient for converting deflection sensitivity, M_{SEM} is the magnification of the SEM, V_{acc} is acceleration voltage for accelerating the

primary electron beam 1, L is the distance between the upper deflector 20 and the specimen 13. Image shifting deflecting intensity V_{IS} given to the lower deflector 30 is expressed by the following expression.

$$V_{IS} = K_2 I_{IS}$$

where K_2 is conversion coefficient for converting deflection sensitivity. The angle between the direction of a magnetic field created by the upper deflector 20, i.e., a magnetic deflector, and that of an electric field created by the lower deflector 30, i.e., an electrostatic deflector, is about 90°. This angle between the directions differs from 90° when a magnetic field is created above the objective 10. This angle can be previously determined by numerical simulation or experiments.

Secondary signal electrons 2 are generated when the specimen 13 is irradiated with the primary electron beam 1. The secondary signal electrons 2 include secondary electrons and reflected electrons. The electric field created in a space between the objective 10 and the specimen 13 acts as an acceleration electric field on the secondary signal electrons 2. Therefore, the secondary signal electrons 2 are attracted to the electron beam passing aperture of the objective 10. The secondary signal electrons 2 travel upward being subjected to the

focusing action of the magnetic field of the objective 10.

The secondary signal electrons having high energy collide

against a conversion electrode 16, whereby secondary

electrons 3 are emitted. A positive high voltage of about

10 kV is applied to a scintillator 17. The scintillator

17 attracts (deflects) the secondary electrons 3 and emits

light. A secondary electron detector, not shown, that

detects secondary electrons guides the light emitted by

the scintillator 17 by a light guide to a photomultiplier,

the photomultiplier converts the light into a

corresponding electric signal, the electric signal is

amplified and the amplified electric signal is used for

the brightness modulation of a CRT.

The principle and advantages of the SEM in this

embodiment will be specifically described with reference

to Figs. 2, 9 and 10. Fig. 9 shows a general SEM for

semiconductor wafer inspection, and paths of secondary

electrons. Fig. 9 shows an observation mode in which the

specimen 13 is observed at a high magnification and image

shifting is not used. In this observation mode, the

primary electron beam 1 falls on the specimen 13 at a

position very close to the optical axis and hence the

high-energy accelerated secondary electrons 2 fall in

regions near the optical axis on the conversion electrode

16. Since the conversion electrode 16 is provided with a

central aperture through which the primary electron beam 1

passes, some secondary electrons 2a travel through the

central aperture of the conversion electrode 16 and are

not detected. Consequently, an image having irregular

brightness is formed. Fig. 10 shows an observation mode

in which the specimen 13 is observed at a high

magnification and image shifting is used. Secondary

electrons 2 emitted from a position to which an image is

shifted pass through a retarding electric field, not shown,

and the objective 10, and travel along a path slightly

deviating from the optical axis and fall in a region not

including the central aperture on the conversion electrode

16.

Since the range of deflection of the primary

electron beam 1 is limited by the central aperture of the

conversion electrode 16, the central aperture of the

conversion electrode 16 cannot be excessively reduced.

The diameter of the central aperture of the conversion

electrode 16 is, for example, 3 mm. Since the optical

magnification of the objective 10 is, for example, 50×, an

image shifting distance, for example, on the order of 60

μm is necessary to enable the secondary electrons fall in

regions not including the central aperture on the

conversion electrode 16. On the other hand, ordinary

image shifting deteriorates resolution by off-axis

aberration when the image shifting distance is greater
than 10 μm. Therefore, it is difficult to observe an
image of a high resolution when image shifting is executed.

The SEM in this embodiment employs a multipole
electrostatic deflector as the lower image shifting
deflector and forms the electrostatic deflector on the
effective principal plane of the objective to achieve the
efficient detection of the secondary electrons without
causing significant deterioration of resolution, even if
an image shifting amount is great. In the SEM shown in
Fig. 1, a magnetic lens is formed by the objective 10 and
an electrostatic lens is formed by the retarding voltage
15 applied to the specimen 13 in the vicinity of the
specimen 13. Although the magnetic and the electrostatic
lens are shown separately in Fig. 2, actually, the
magnetic and the electrostatic lens are superposed. Fig.
2A shows deflecting forces exerted by the magnetic and the
electrostatic lens on the primary electrons traveling
along an off-axis path. The deflecting force FB0 of the
objective acts in a rotating direction and the deflecting
force FE0 of the electrostatic lens acts in a radial
direction. The deflecting force FB0 is always greater
than the deflecting force FE0 (FB0 > FE0). Fig. 2B shows
the so-called moving objective that cancels deflecting
forces by superposing lateral deflecting electric field

FE1 and a magnetic field FB1 on the lens electric field
and magnetic field. Since the deflecting forces are
cancelled individually, i.e., FB0 + FB1 = 0 and FE0 + FE1
= 0, off-axis aberration is suppressed to the least extent.
Fig. 2C shows the cancellation of deflecting force only by
the deflecting electric field. Deflecting force acting on
the primary electrons can be cancelled by: FB0 + FE2 = 0
and FE0 + FB1 = 0. Since the secondary electrons travel
in the reverse direction, the deflecting force of the
magnetic field is reversed. Generally, FB0 + FE2 = 2 ×
FE0 and FE0 + FE1 = 0, and a comparatively large
deflecting force remains. Fig. 2D shows the cancellation
of the deflecting force only by superposition of the
deflecting magnetic field. For the primary electrons, FB0
+ FB1 = 0 and FE0 + FE1 = 0. For the secondary electrons,
the deflecting force of the magnetic field is reversed
because the secondary electrons travel in the reverse
direction. Generally, FB0 + FE2 = 0 and FE0 + FB2 = 2 ×
FE0, and a comparatively small deflecting force remains.
As obvious from Figs. 2A to 2D, the superposition of the
deflecting electric field shown in Fig. 2C is advantageous
to meet both the elimination of the off-axis aberration of
the primary electrons and the deflection of the secondary
electrons.

When observing an image with the image shifted by a

fixed distance on the basis of the foregoing principle by the SEM in this embodiment, the secondary electrons 2 are caused to travel along a path extending apart from the optical path so that most of the secondary electrons fall in a region not including the central aperture of the conversion electrode 16 on the conversion electrode 16, to suppress off-axis aberration due to image shifting and to improve secondary electron detecting efficiency. In some cases, image shifting deflection improves the secondary electron detecting efficiency in a SEM employing the retarding technique and it is desirable to set an observation point with awareness of such a fact.

It is possible to prevent the secondary electrons from passing the central aperture of the conversion electrode 16 by disposing an energy filter 60 including a plurality of layers of meshes below the conversion electrode 16 with respect to the traveling direction of the primary electron beam, whereby energy discriminating ability is improved. In the SEM in this embodiment, a secondary electron detector, not shown, may be interposed between the energy filter 60 and the objective 10 to catch all the secondary electrons that collide against the meshes of the energy filter 60 and do not reach the conversion electrode 16.

When there is not any retarding electric field or

the retarding electric field is sufficiently small, only the reflected electrons pass the electron beam passing aperture of the objective 10. The reflected electrons have high energy. Positions at which the reflected electrons fall on the conversion electrode 16 are dependent on angle at which the electrons are reflected by the specimen 13 and energy of the reflected electrons. Therefore, information represented by the selected reflected electrons can be obtained in a high sensitivity by disposing an aperture filter 62 below the conversion electrode 16 with respect to the traveling direction of the primary electron beam. When the reflected electrons reflected in a substantially perpendicular direction are selected, an image of high contrast of a specimen having a specific atomic number can be observed in a high resolution. In the conventional SEM, the path of the reflected electrons and the path of the primary electrons overlap each other and hence the detection of the reflected electrons is difficult.

Substantially the same effect can be expected by making only a part of the conversion electrode 16 emit secondary electrons instead of employing the aperture filter 62. In such a case, it is preferable to coat the conversion electrode 16 excluding a part of the same with carbon that emit secondary electrons at a low efficiency.

Fig. 3 shows a SEM in a second embodiment according
to the present invention. In the SEM in the first
embodiment, the objective 10 cause slight off-axis
aberration because deflecting force is exerted on the
secondary electrons 2. The off-axis aberration is a
significant problem that affects adversely to observation
in a high resolution. In the third embodiment, a Wien
filter 62 adjusted so as to cancel off-axis aberration
caused by an objective 10 is disposed on the side of an
electron source with respect to a conversion electrode 16
to avoid the problem attributable to off-axis aberration.

Fig. 4 shows a SEM in a third embodiment according
to the present invention. The SEM in the third embodiment
is provided with, in addition to two scanning deflectors
18 and 19 of a general SEM disposed at two stages, image
shifting deflectors 20 and 30 in accordance with the
present invention. A primary electron beam 1 traveled
through a diaphragm 11 is deflected for two-dimensional
scanning on a specimen 13 by the scanning deflectors 18
and 19. A deflection control power supply 40 gives a
deflecting intensity I_{IS} corresponding to a shifting
distance to the upper image shifting deflector 20 for
image shifting and gives a deflecting intensity V_{IS}
adjusted so as to make a primary electron beam 1 travel
straight through an objective 10 to the lower image

shifting deflector 30.

Thus, the image shifting deflectors 20 and 30 can be easily incorporated into the general SEM to improve image shifting function, resolution and accuracy of dimensional measurement.

The image shifting deflectors 20 and 30 will be described with reference to Figs. 4 and 5. The upper image shifting deflector 20 is the same in construction as a conventional scanning deflector. The upper image shifting deflector 20 has scanning coils 21 to 24 are cosine distributed winding coils to create a uniform deflecting magnetic field around the optical axis of the SEM. The four quadrant coils are disposed in a circle. Coil currents are regulated in proportion to the cosine of the angle ϕ between an electron beam deflecting direction and the position of the scanning coils to deflect the primary electron beam 1 in a desired direction. Usually, currents of the same absolute value and opposite directions are supplied to the opposite scanning coils 21 and 23, respectively. Therefore, currents can be supplied to both the scanning coils 21 and 23 from a single power supply by connecting the scanning coils 21 and 23 to the power supply in opposite ways of connection, respectively. Similarly, currents can be supplied to the opposite scanning coils 22 and 24 by a single power supply.

The lower image shifting deflector 30 is an octupole electrostatic deflector. Since the lower image shifting deflector 30 is disposed in a narrow space between the objective 10 and the specimen 13, the lower image shifting deflector 30 is formed in the shape of a disk. Although the octupole electrostatic deflector can be constructed by assembling eight 1/8 electrode sectors, the octupole electrostatic deflector is formed by the following method to assemble the same in a high accuracy and to reduce assembling costs. An electron beam passing aperture is formed in an insulating disk of several millimeters in thickness. Insulating slits are formed in the insulating disk so as to extend radially from the electron beam passing aperture. Eight electrostatic deflecting electrodes 31 to 38 are formed by coating the front and the back surface of a part of the disk around the electron beam passing aperture and the side surfaces of the electron beam passing aperture and the insulating slits with a conductive material by a vapor deposition process or a plating process. Voltages to be applied to the electrodes 31 to 38 are regulated in proportion to the cosine of the angle θ between an electron beam deflecting direction and the position of the electrodes 31 to 38 to deflect an electron beam by a desired distance in a desired direction. An angular displacement $\Delta\phi$ corresponds

to the angle of rotation of a primary electron beam caused

by a lens magnetic field created in a space between the

upper image shifting deflector 20 and the lower image

shifting deflector 30.

Figs. 7 and 8 show lower image shifting deflectors

30 suitable for use in combination with an objective 10

having a principal plane on a level above the bottom

surface of the objective 10, i.e., a level in the electron

beam passing aperture of the objective 10. The lower

image shifting deflector 30 shown in Fig. 7 has a

funnel-shaped insulating base plate and the base plate is

inserted from above the objective 10 in the electron beam

passing aperture. A head part of the insulating base

plate is divided into eight divisions and coated with a

conductive material by the foregoing method. A shielding

electrode 39 prevents the charging effect of an insulating

part of the lower image shifting deflector 30 and the

creation of a deflecting electric field in a region not

affected by an objective magnetic field. The lower image

shifting deflector 30 shown in Fig. 8 is inserted from

below an objective 10 in an electron beam passing aperture

formed in the objective 10. The insulating base plate of

the lower image shifting deflector 30 has a flat, annular

peripheral part and a cylindrical central part extending

from a central portion of the peripheral part. The

peripheral part and the central part of the base plate are
divided into eight divisions, and coated with a conductive
material by the foregoing method. In some cases, the
cylindrical part is extended not only toward the objective
10 but also toward the specimen 13 according to the
distribution of the objective magnetic field. A
deflection control power supply 40 applies a voltage to
the lower image shifting deflector 30 relative to a ground
potential to deflect an electron beam. The surface
electric field of the specimen 13 can be adjusted by off-
setting a reference potential by a power supply 49, which
is effective in charging and adjusting surface potential
for the observation of an insulating specimen. The lower
image shifting deflector 30 can be easily installed also
when the SEM is provided with a height measuring device
that measures the height of the specimen 13 by using a
laser beam. A laser light source 51 projects a laser beam
52 obliquely to the specimen 13. The laser beam 52
reflected by the specimen 13 is detected by a position
sensor 53. The position of the reflected laser beam 52 on
the position sensor 53 varies according to the height of
the specimen 13. The variation of the height of the
specimen 13 is determined through the measurement of the
variation of the position of the reflected laser beam 52
on the position sensor 53. The lower image shifting

deflector 30, i.e., the octupole electrostatic deflector, can be easily disposed so that the laser beam 52 and the reflected laser beam 52 may pass the insulating slits of the lower image shifting deflector 30.

In the SEM in this embodiment, the upper image shifting deflector deflects the electron beam off the optical axis taking the Lorentz force of the objective into consideration, and the lower image shifting deflector executes electrostatic deflection of the electron beam so that the axial deviation of the electron beam by the Lorentz force may be suppressed and the electron beam travels straight toward the specimen. Therefore, off-axis aberration due to a large angle of deflection of the electron beam can be suppressed and resolution can be improved.

Since an electrostatic deflector is used as the lower image shifting deflector disposed between the lower magnetic pole of the objective of an open lower magnetic pole type and the specimen, the electron beam can be deflected without increasing the short focal length of the objective.

The SEM in this embodiment reduces aberration by employing the objective having a short focal length and reduces off-axial aberration by controlling the angle of deflection for image shifting.

Fig. 11 is a view of assistance in explaining a SEM
in a fourth embodiment according to the present invention.
Fig. 11 shows typically a deflection range 101 for image
shifting. The SEM as shown in Fig. 1 is provided with a
controller, not shown. The controller sets values of
parameters including observation positions and
magnification, and controls a mirror included in the SEM
on the basis of the set values. A SEM for inspecting
semiconductor wafers needs to observe a plurality of
points on the surface of a semiconductor wafer. Recipe
specifying conditions for the observation of the plurality
of points are set beforehand or the recipe is set manually.

A plurality of high-magnification observation
regions 103 can be set in the deflection range 101 in
which the electron beam is deflected by image shifting
deflectors 20 and 30. As mentioned above, most secondary
electrons from a central point 102 of the deflection range
101, i.e., a point corresponding to a primary electron
beam 1, pass through the aperture of a conversion
electrode 16, and an image of a specimen, having irregular
brightness is formed. It is desirable to provide the SEM
with a sequence that inhibits setting of a
high-magnification observation region 103 at the center
102 of the deflection range 101. For example, when the
SEM is provided with a sequence that sets a desired

high-magnification observation region among

low-magnification images, the foregoing problem can be

prevented by making the setting of a high-magnification

observation region 103 at the center 102 of the deflection

range impossible or by generating a warning requesting

moving the stage and resetting the high-magnification

observation region 103. When the SEM is provided with

recipe specifying operations for multiple-point

observation, it is desirable to specify conditions for

controlling the stage so that the high-magnification

observation region 102 may not be located at the center of

the deflection range, to generate a warning when

conditions are set so as to locate the high-magnification

observation region 102 at the center of the deflection

region or to inhibit the setting of such conditions. The

operator is able to carry out operations for setting the

high-magnification region at a position other than the

center of the deflection range 101 without depending on

warnings or the like when a typical image of the

deflection region 101 of the image shifting deflectors as

shown in Fig. 11 is displayed on the screen of a display,

not shown.

The SEM in this embodiment is able to form an image

of a high resolution and to measure dimensions in a high

accuracy even if the distance of image shifting is great.

In particular, in semiconductor device fabricating processes that process a wafer having a large area and provided with very minute circuit elements, the SEM is able to achieve precision inspection at a high throughput.